

# Flavour Theory and the LHC Era

Andrzej J. Buras

Physik-Department, Technische Universität München, D-85748 Garching, Germany  
TUM Institute of Advanced Study, Lichtenbergstr. 2a, D-85748 Garching, Germany

DOI: will be assigned

This decade should make a significant progress towards the Theory of Flavour and the main goal of this talk is to transfer this believe to my colleagues in the particle physics community. Indeed a significant part of this decade could turn out to be the Flavour Era with participation of the LHC, Belle II, Super-Flavour-Facility and dedicated Kaon and lepton flavour violation experiments. Selected superstars of flavour physics listed below will play a prominent role in these events. In this writeup the leading role is played by the *prima donna* of 2010: CP violation in  $B_s$  system.

## 1 Introduction

In our search for a fundamental theory of elementary particles we need to improve our understanding of flavour [1, 2]. This is clearly a very ambitious goal that requires the advances in different directions as well as continuous efforts of many experts day and night, as depicted with the help of a "Flavour Clock" in Figure 1.

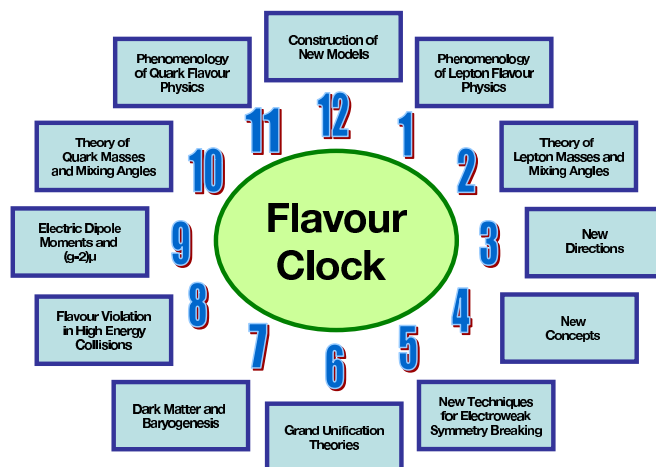


Figure 1: Working towards the Theory of Flavour around the Flavour Clock.

Despite the impressive success of the CKM picture of flavour changing interactions [3] in which also the GIM mechanism [4] for the suppression of flavour changing neutral currents (FCNC) plays a very important role, there are many open questions of theoretical and experimental nature that should be answered before we can claim to have a theory of flavour. Among the basic questions in flavour physics that could be answered in the present decade are the following ones:

1. What is the fundamental dynamics behind the electroweak symmetry breaking that very likely plays also an important role in flavour physics?
2. Are there any new flavour symmetries that could help us to understand the existing hierarchies of fermion masses and the hierarchies in the quark and lepton flavour violating interactions?
3. Are there any flavour violating interactions that are not governed by the SM Yukawa couplings? In other words, is Minimal Flavour Violation (MFV) the whole story?
4. Are there any additional *flavour violating* CP-violating (CPV) phases that could explain certain anomalies present in the flavour data and simultaneously play a role in the explanation of the observed baryon-antibaryon asymmetry in the universe (BAU)?
5. Are there any *flavour conserving* CPV phases that could also help in explaining the flavour anomalies in question and would be signalled in this decade through enhanced electric dipole moments (EDMs) of the neutron, the electron and of other particles?
6. Are there any new sequential heavy quarks and leptons of the 4th generation and/or new fermions with exotic quantum numbers like vectorial fermions?
7. Are there any elementary neutral and charged scalar particles with masses below 1 TeV and having a significant impact on flavour physics?
8. Are there any new heavy gauge bosons representing an enlarged gauge symmetry group?
9. Are there any relevant right-handed (RH) weak currents that would help us to make our fundamental theory parity conserving at short distance scales well below those explored by the LHC?
10. How would one successfully address all these question if the breakdown of the electroweak symmetry would turn out to be of a non-perturbative origin?

An important question is the following one: will some of these questions be answered through the interplay of high energy processes explored by the LHC with low energy precision experiments or are the relevant scales of fundamental flavour well beyond the energies explored by the LHC and future colliders in this century? The existing tensions in some of the corners of the SM and still a rather big room for new physics (NP) contributions in rare decays of mesons and leptons and CP-violating observables including in particular EDMs give us hopes that indeed several phenomena required to answer at least some of these questions could be discovered in this decade.

## 2 Superstars of Flavour Physics in 2010-2015

In this decade we will be able to resolve the short distance scales by more than an order of magnitude, extending the picture of fundamental physics down to scales  $5 \cdot 10^{-20}$  m with the help of the LHC. Further resolution down to scales as short as  $10^{-21}$  m or even shorter scales should be possible with the help of high precision experiments in which flavour violating processes will play a prominent role.

As far as high precision experiments are concerned a number of selected processes and observables will in my opinion play the leading role in learning about the NP in this new territory. This selection is based on the sensitivity to NP and theoretical cleanliness. The former can be increased with the increased precision of experiments and the latter can improve with the progress in theoretical calculations, in particular the non-perturbative ones like the lattice simulations.

My superstars for the coming years are as follows:

- The mixing induced CP-asymmetry  $S_{\psi\phi}(B_s)$  that is tiny in the SM:  $S_{\psi\phi} \approx 0.04$ . The asymmetry  $S_{\phi\phi}(B_s)$  is also important. It is also very strongly suppressed in the SM and is sensitive to NP similar to the one explored through the departure of  $S_{\phi K_S}(B_d)$  from  $S_{\psi K_S}(B_d)$  [5].
- The rare decays  $B_{s,d} \rightarrow \mu^+ \mu^-$  that could be enhanced in certain NP scenarios by an order of magnitude with respect to the SM values.
- The angle  $\gamma$  of the unitarity triangle (UT) that can be precisely measured through tree level decays.
- $B^+ \rightarrow \tau^+ \nu_\tau$  that is sensitive to charged Higgs particles.
- The rare decays  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  and  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  that belong to the theoretically cleanest decays in flavour physics.
- Numerous angular symmetries and asymmetries in  $B \rightarrow K^* l^- l^-$ .
- Lepton flavour violating decays like  $\mu \rightarrow e \gamma$ ,  $\tau \rightarrow e \gamma$ ,  $\tau \rightarrow \mu \gamma$ , decays with three leptons in the final state and  $\mu - e$  conversion in nuclei.
- Electric dipole moments of the neutron, the electron, atoms and leptons.
- Anomalous magnetic moment of the muon  $(g-2)_\mu$  that indeed seems to be "anomalous" within the SM even after the inclusion of radiative corrections.
- The ratio  $\varepsilon'/\varepsilon$  in  $K_L \rightarrow \pi\pi$  decays which is known experimentally within 10% and which should gain in importance in this decade due to improved lattice calculations.

Clearly, there are other stars in flavour physics but I believe that the ones above will play the crucial role in our search for the theory of flavour. Having experimental results on these decays and observables with sufficient precision accompanied by improved theoretical calculations will exclude several presently studied models reducing thereby our exploration of short distance scales to a few avenues.

In the rest of this presentation I will discuss some of these decays in the context of the basic questions in flavour physics listed previously. In particular we will collect a number of

messages on NP which result from the recent and not so recent model independent studies and detailed analyses of concrete numerous beyond the SM models (BSM). In this context the role of correlations between various observables implying various patterns of flavour violation characteristic for various concrete models should be strongly emphasized. Recent reviews can be found in [1, 2]. In the context of  $B_{s,d}$ -mixing and related NP see a very detailed recent analysis in [6].

### 3 Beyond the Standard Model (BSM)

During the last 35 years several extensions of the SM have been proposed and analyzed in the rich literature. In particular in the last 10 years, after the data on  $B_{d,s}$  decays,  $B_{d,s}^0 - \bar{B}_{d,s}^0$  mixing and related CP violation improved considerably and the bounds on lepton flavour violating decays became stronger, useful model independent analyses of FCNC processes could be performed. Moreover several extensive analyses of the full spectrum of flavour violating processes in the context of specific BSM scenarios have been published.

#### 3.1 Minimal Flavour Violation

Among the model independent approaches in flavour physics the most prominent role is played by MFV [7, 8] in which flavour violation including CP violation originates entirely from the SM Yukawa couplings. This approach naturally suppresses FCNC processes to the level observed experimentally even in the presence of new particles with masses of a few hundreds GeV. It also implies specific correlations between various observables, which are most stringent in the so-called constrained MFV (CMFV) [8] in which only the SM operators are assumed to be relevant. Basically MFV reduces to CMFV when only one Higgs doublet is present.

A particularly interesting set-up is obtained introducing flavour-blind CPV phases compatible with the MFV symmetry principle [9, 10, 11, 12, 13].

As recently shown in [14], the general formulation of the MFV hypothesis with flavour-blind CPV phases (FBPh) applied to a general two Higgs doublet model is very effective in suppressing FCNCs to a level consistent with experiments, leaving open the possibility of sizable non-standard effects also in CPV observables. In what follows we will call this model  $2\text{HDM}_{\overline{\text{MFV}}}$  with the "bar" on MFV indicating the presence of FBPhs. As discussed in [14], the  $2\text{HDM}_{\overline{\text{MFV}}}$  can accommodate a large CP-violating phase in  $B_s$  mixing, as hinted by CDF and D0 data [15, 16, 17], while ameliorating simultaneously the observed anomaly in the relation between  $\epsilon_K$  and  $S_{\psi K_S}$  [18, 19].

On general grounds, it is natural to expect that FBPhs contribute also to CPV flavour-conserving processes, such as the EDMs. Indeed, the choice adopted in [7] to assume the Yukawa couplings as the unique breaking terms of both the flavour symmetry and the CP symmetry, was motivated by possibly too large effects in EDMs with generic FBPhs. This potential problem has indeed been confirmed by the recent model-independent analysis in [20].

In [21] the correlations between EDMs and CP violation in  $B_{s,d}$  mixing in  $2\text{HDM}_{\overline{\text{MFV}}}$  including FBPhs in Yukawa interactions and the Higgs potential have been studied in detail. It has been shown that in both cases the upper bounds on EDMs of the neutron and the atoms do not forbid sizable non-standard CPV effects in  $B_s$  mixing. However, if a large CPV phase in  $B_s$  mixing will be confirmed, this will imply hadronic EDMs very close to their present experimental bounds, within the reach of the next generation of experiments, as well as  $Br(B_{s,d} \rightarrow \mu^+ \mu^-)$

typically largely enhanced over its SM expectation. The two flavour-blind CPV mechanisms can be distinguished through the correlation between  $S_{\psi K_S}$  and  $S_{\psi\phi}$  that is strikingly different if only one of them is relevant. Which of these two CPV mechanisms dominates depends on the precise values of  $S_{\psi\phi}$  and  $S_{\psi K_S}$ , as well as on the CKM phase (as determined by tree-level processes). Current data seems to show a mild preference for a *hybrid* scenario where both these mechanisms are at work. I will be a bit more explicit about this result below.

### 3.2 Beyond Minimal Flavour Violation

There is a number of explicit BSM models that introduce new sources of flavour violation and CP violation beyond those present in the MFV framework discussed above. Among them the Littlest Higgs Model with T-parity (LHT), the Randall-Sundrum model without and with custodial protection (RSc), various supersymmetric flavour models,  $Z'$ -models, models with vectorial new quarks, the SM extended by the fourth sequential generation of quarks and leptons (SM4) and multi-Higgs doublet models are the ones in which most extensive flavour analyses have been performed. Most of them have been reviewed in some details in [1], where the relevant references can be found. I will concentrate in this presentation on very recent developments and will only recall some of the most interesting results of these older analyses if necessary.

During the second half of 2009 and also in 2010 the flavour analyses in the framework of the 2HDM with and without MFV and also the SM4 became popular. The 2HDM<sub>MFV</sub> has been already briefly discussed above. The SM4 introduces three new mixing angles  $s_{14}$ ,  $s_{24}$ ,  $s_{34}$  and two new phases in the quark sector and can still have a significant impact on flavour phenomenology. Most recent extensive analyses of FCNC processes in the SM4 can be found in [22, 23, 24, 25]. More about it later.

Next, let me mention an effective theory approach in which the impact of RH currents in both charged- and neutral-current flavour-violating processes has been analysed [26]. While RH currents are present in several supersymmetric flavour models, in RS models and of course in left-right symmetric models based on the gauge group  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$  (see [27, 28] for most recent papers), the recent phenomenological interest in these models originated in tensions between inclusive and exclusive determinations of the elements of the CKM matrix  $|V_{ub}|$  and  $|V_{cb}|$ . It could be that these tensions are due to the underestimate of theoretical and/or experimental uncertainties. Yet, it is a fact, as pointed out and analyzed recently in particular in [29, 30, 31], that the presence of RH currents could either remove or significantly weaken some of these tensions, especially in the case of  $|V_{ub}|$ . Implications of this setup for other observables, in particular FCNC processes without specifying the fundamental theory in detail but only assuming its global symmetry and the pattern of its breakdown have been analyzed in [26]. As we will see this approach can be considered as a minimal flavour violating scenario in the RH sector and will be called RHMFV in what follows. I will return to the results of this work below.

Finally, recent studies of flavour violating processes in models for fermion masses and mixings [32, 33, 34], indicate that a full theory of flavour has to involve at a certain level non-MFV interactions.

## 4 Waiting for Signals of NP in FCNC Processes

### 4.1 General Remarks

The last decade has established that flavour-changing and CPV processes in  $B_{s,d}$  and K systems are on the whole well described by the SM. The same applies to electroweak precision tests. This implies automatically tight constraints on flavour-changing phenomena beyond the SM and a potential problem for a natural solution of the hierarchy problem and other problems listed in the Introduction, several of which require the presence of NP not far from the electroweak scale.

It is evident from various model-independent studies that NP at the TeV scale must have a non-generic flavour structure in order to satisfy existing constraints. Moreover, in order to avoid fine tuning of parameters, natural protection mechanisms suppressing FCNCs generated by NP are required. In addition to MFV and GIM, RS-GIM, T-parity in Littlest Higgs models, alignment and degeneracy, most familiar from supersymmetric models and generally flavour symmetries (abelian and non-abelian) have been invented for this purpose. Last but certainly not least, custodial symmetries, like the ones related to the Higgs system and relevant for electroweak precision tests, can be used to suppress specific flavour-violating neutral gauge boson couplings.

It should be emphasized that only protection mechanisms that are stable under radiative corrections can be considered as solutions to flavour problems and considerations of protection mechanisms only at tree level are insufficient. In this context let us recall that the standard assignment of the  $SU(2)_L \times U(1)_Y$  quark charges, identified long ago by Glashow, Iliopoulos, and Maiani (GIM) [4], forbids tree-level flavour-changing couplings of the quarks to the SM neutral gauge bosons. This mechanism is only violated at the loop level and the FCNC processes are strongly suppressed by the products of CKM elements and mass splittings of quarks or leptons carrying the same electric charge. Only in processes involving the top quark exchanges is GIM strongly broken but in a calculable manner and the pattern of this breakdown seems to agree with experiment although the tests of this pattern have to be still very much improved.

In the case of only one Higgs doublet, namely within the SM, this structure is effective also in eliminating possible dimension-four FCNC couplings of the quarks to the Higgs field. While the  $SU(2)_L \times U(1)_Y$  assignment of quarks and leptons can be considered as being well established, much less is known about the Higgs sector of the theory. In the presence of more than one Higgs field the appearance of tree-level FCNC is not automatically forbidden by the standard assignment of the  $SU(2)_L \times U(1)_Y$  fermion charges: additional conditions have to be imposed on the model in order to guarantee a sufficient suppression of FCNC processes [35, 36]. The absence of renormalizable couplings contributing at the tree level to FCNC processes, in multi-Higgs models, goes under the name of Natural Flavour Conservation (NFC) hypothesis.

It has been pointed out recently [14] that the MFV hypothesis is more stable in suppressing FCNCs than the hypothesis of NFC alone when quantum corrections are taken into account. Indeed the NFC hypothesis is usually based on a  $U(1)_{PQ}$  symmetry that has to be broken in order to avoid massless scalars. NFC can also be enforced by a  $Z_2$  symmetry. However, it turns out that also this symmetry is insufficient to protect FCNCs when radiative corrections are considered. On the other hand MFV hypothesis based on continuous flavour symmetries is more powerful. Thus 30 years after the seminal papers of Glashow, Weinberg and Paschos, the hypothesis of NFC can be replaced by the more powerful and more general hypothesis of MFV. Other recent interesting analyzes of 2HDMs can be found in [37, 38, 39, 40].

## 4.2 Three Strategies in Waiting for NP in Flavour Physics

Particle physicists are waiting eagerly for a solid evidence of NP for the last 30 years. Except for neutrino masses, the BAU and dark matter, no clear signal emerged so far. While waiting several strategies for finding NP have been developed. They can be divided roughly into three classes.

### 4.2.1 Precision calculations within the SM

Here basically the goal is to calculate the background to NP coming from the known dynamics of the SM. At first sight this approach is not very exciting. Yet, in particular in flavour physics, where the signals of NP are generally indirect, this approach is very important. From my point of view, being involved more than one decade in calculations of higher order QCD corrections [41], I would claim that for most interesting decays these perturbative and renormalization group improved calculations reached already the desired level. The most advanced NNLO QCD calculations have been done for  $B \rightarrow X_s \gamma$ ,  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ,  $B \rightarrow X_s l^+ l^-$  and recently for  $\varepsilon_K$  [42]. See also the two loop electroweak contributions to  $K \rightarrow \pi \nu \bar{\nu}$  [43].

The main progress is now required from lattice groups. Here the main goals for the coming years are more accurate values of weak decay constants  $F_{B_{d,s}}$  and various  $\hat{B}_i$  parameters relevant for  $B_{d,s}$  physics. For  $K^0 - \bar{K}^0$  mixing the relevant parameter  $\hat{B}_K$  is now known with an accuracy of 4% [44]. An impressive achievement. Let us hope that also the parameters  $B_6$  and  $B_8$ , relevant for  $\varepsilon'/\varepsilon$  will be known with a similar accuracy within this decade.

Clearly further improvements on the hadronic part of two-body non-leptonic decays is mandatory in order to understand more precisely the direct CP violation in  $B_{s,d}$  decays.

### 4.2.2 The Bottom-Up Approach

In this approach one constructs effective field theories involving only light degrees of freedom including the top quark in which the structure of the effective Lagrangians is governed by the symmetries of the SM and often other hypothetical symmetries. This approach is rather powerful in the case of electroweak precision studies and definitely teaches us something about  $\Delta F = 2$  transitions. However, except for the case of MFV and closely related approaches based on flavour symmetries, the bottom-up approach ceases, in my view, to be useful in  $\Delta F = 1$  decays, because of very many operators that are allowed to appear in the effective Lagrangians with coefficients that are basically unknown [45]. In this approach then the correlations between various  $\Delta F = 2$  and  $\Delta F = 1$  observables in  $K$ ,  $D$ ,  $B_d$  and  $B_s$  systems are either not visible or very weak, again except MFV, CMFV or closely related approaches. Moreover the correlations between flavour violation in low energy processes and flavour violation in high energy processes to be studied soon at the LHC is lost. Again MFV belongs to a few exceptions.

### 4.2.3 The Top-Down Approach

My personal view shared by some of my colleagues is that the top-down approach is more useful in flavour physics. Here one constructs first a specific model with heavy degrees of freedom. For high energy processes, where the energy scales are of the order of the masses of heavy particles one can directly use this “full theory” to calculate various processes in terms of the fundamental parameters of a given theory. For low energy processes one again constructs the low energy theory by integrating out heavy particles. The advantage over the previous approach is that



now the coefficients of the resulting local operators are calculable in terms of the fundamental parameters of this theory. In this manner correlations between various observables belonging to different mesonic systems and correlations between low energy and high-energy observables are possible. Such correlations are less sensitive to the free parameters than separate observables and represent patterns of flavour violation characteristic for a given theory. These correlations can in some models differ strikingly from the ones of the SM and of the MFV approach.

### 4.3 Anatomies of explicit models

Having the last strategy in mind my group at the Technical University Munich, consisting dominantly of diploma students, PhD students and young post-docs investigated in the last decade flavour violating processes with the emphasis put on FCNC processes, in the following models: CMFV, MFV, MFV-MSSM,  $Z'$ -models, general MSSM, a model with a universal flat 5th dimension, the Littlest Higgs model (LH), the Littlest Higgs model with T-parity (LHT), SUSY-GUTs, Randall-Sundrum model with custodial protection (RSc), flavour blind MSSM (FBMSSM), three classes of supersymmetric flavour models with the dominance of left-handed currents ( $\delta$ LL model), the dominance of right-handed currents (AC model) and models with equal strength of left- and right-handed currents (RVV2 and AKM models), the last comments applying only to the NP part. This year we have analyzed the SM4, the 2HDM $_{\overline{\text{MFV}}}$  and finally quark flavour mixing with RH currents in an effective theory approach RHMFV. These analyses were dominated by quark flavour physics, but in the case of the LHT, FBMSSM, supersymmetric flavour models and the SM4 lepton flavour violation has also been studied in detail.

As a partial review of this work appeared already in [1] with various correlations presented in Figures 5 - 11 of that paper I will not discuss them in detail here. In [1] numerous references (301) to our papers and studies by other groups can be found. The detailed discussion of the supersymmetric flavour models ( $\delta$ LL, AC, RVV2, AKM) can be found in [32].

The “DNA” of flavour physics effects for the most interesting observables constructed in [32] and extended by the recent results obtained in the SM4 is presented in Table 1. This table only indicates whether large, moderate or small NP effects in a given observable are still allowed in a given model but does not exhibit correlations between various observables characteristic for a given model. Such correlations can be found in [1] and original papers quoted there. I will summarize the most striking ones later on.

### 4.4 $\varepsilon_K$ -anomaly and related tensions

It has been pointed out in [19] that the SM prediction for  $\varepsilon_K$  implied by the measured value of  $S_{\psi_{K_S}} = \sin 2\beta$ , the ratio  $\Delta M_d/\Delta M_s$  and the value of  $|V_{cb}|$  turns out to be too small to agree well with experiment. This tension between  $\varepsilon_K$  and  $S_{\psi_{K_S}}$  has been pointed out from a different perspective in [18]. These findings have been confirmed by a UTfitters analysis [46]. The CKMfitters having a different treatment of uncertainties find less significant effects [6].

The main reasons for this tension are on the one hand a decreased value of the relevant non-perturbative parameter  $\hat{B}_K = 0.724 \pm 0.008 \pm 0.028$  [44] resulting from unquenched lattice calculations and on the other hand the decreased value of  $\varepsilon_K$  in the SM arising from a multiplicative factor, estimated first to be  $\kappa_\varepsilon = 0.92 \pm 0.02$  [19]. This factor took into account the departure of  $\phi_\varepsilon$  from  $\pi/4$  and the long distance (LD) effects in  $\text{Im}\Gamma_{12}$  in the  $K^0 - \bar{K}^0$  mixing. The recent inclusion of LD effects in  $\text{Im}M_{12}$  modified this estimate to  $\kappa_\varepsilon = 0.94 \pm 0.02$  [47]. Very recently



	AC	RVV2	AKM	$\delta$ LL	FBMSSM	LHT	RSc	4G
$D^0 - \bar{D}^0$	★★★★	★	★	★	★	★★★★	?	★★
$\epsilon_K$	★	★★★★	★★★★	★	★	★★	★★★★	★★
$S_{\psi\phi}$	★★★★	★★★★	★★★★	★	★	★★★★	★★★★	★★★★
$S_{\phi K_S}$	★★★★	★★	★	★★★★	★★★★	★	?	★★
$A_{CP}(B \rightarrow X_s \gamma)$	★	★	★	★★★★	★★★★	★	?	★
$A_{7,8}(K^* \mu^+ \mu^-)$	★	★	★	★★★★	★★★★	★★	?	★★
$B_s \rightarrow \mu^+ \mu^-$	★★★★	★★★★	★★★★	★★★★	★★★★	★	★	★★★★
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	★	★	★	★	★	★★★★	★★★★	★★★★
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	★	★	★	★	★	★★★★	★★★★	★★★★
$\mu \rightarrow e \gamma$	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★
$\tau \rightarrow \mu \gamma$	★★★★	★★★★	★	★★★★	★★★★	★★★★	★★★★	★★★★
$\mu + N \rightarrow e + N$	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★
$d_n$	★★★★	★★★★	★★★★	★★	★★★★	★	★★★★	★
$d_e$	★★★★	★★★★	★★	★	★★★★	★	★★★★	★
$(g-2)_\mu$	★★★★	★★★★	★★	★★★★	★★★★	★	?	★

Table 1: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models. ★★★★★ signals large NP effects, ★★ visible but small NP effects and ★ implies that the given model does not predict sizable NP effects in that observable. From [32].

also NNLO-QCD corrections to the QCD factor  $\eta_{ct}$  in  $\epsilon_K$  [42] have been calculated enhancing the value of  $\epsilon_K$  by 3%. Thus while in [19] the value  $|\epsilon_K|_{SM} = (1.78 \pm 0.25) \cdot 10^{-3}$  has been quoted and with the new estimate of LD effects and new input one finds  $|\epsilon_K|_{SM} = (1.85 \pm 0.22) \cdot 10^{-3}$ , including NNLO corrections gives the new value

$$|\epsilon_K|_{SM} = (1.92 \pm 0.25) \cdot 10^{-3}, \quad (1)$$

significantly closer to the experimental value  $|\epsilon_K|_{exp} = (2.23 \pm 0.01) \cdot 10^{-3}$ . This result is compatible with [42, 6] although the central value in (1) is sensitive to the input parameters, in particular the value of  $\sin 2\beta$ .

Consequently, the  $\epsilon_K$ -anomaly softened considerably but it is still alive. Indeed, the  $\sin 2\beta = 0.74 \pm 0.02$  from UT fits is visibly larger than the experimental value  $S_{\psi K_S} = 0.672 \pm 0.023$ . The difference is even larger if one wants to fit  $\epsilon_K$  exactly:  $\sin 2\beta \approx 0.80$  [18, 19].

One should also recall the tension between inclusive and exclusive determinations with the exclusive ones in the ballpark of  $3.5 \cdot 10^{-3}$  and the inclusive ones typically above  $4.0 \cdot 10^{-3}$ .

As discussed in [18, 19] a small negative NP phase  $\varphi_{B_d}$  in  $B_d^0 - \bar{B}_d^0$  mixing would solve some

of these problems. Indeed we have then

$$S_{\psi K_S}(B_d) = \sin(2\beta + 2\varphi_{B_d}), \quad S_{\psi\phi}(B_s) = \sin(2|\beta_s| - 2\varphi_{B_s}), \quad (2)$$

where the corresponding formula for  $S_{\psi\phi}$  in the presence of a NP phase  $\varphi_{B_s}$  in  $B_s^0 - \bar{B}_s^0$  mixing has also been given. With a negative  $\varphi_{B_d}$  the true  $\sin 2\beta$  is larger than  $S_{\psi K_S}$ , implying a higher value on  $|\varepsilon_K|$ , in reasonable agreement with data and a better UT-fit. This solution would favour the inclusive value of  $|V_{ub}|$ .

Now with a universality hypothesis of  $\varphi_{B_s} = \varphi_{B_d}$  [48, 19], a negative  $\varphi_{B_d}$  would automatically imply an enhanced value of  $S_{\psi\phi}$  which in view of  $|\beta_s| \approx 1^\circ$  amounts to roughly 0.04 in the SM. However, in order to be in agreement with the experimental value of  $S_{\psi K_S}$  this type of NP would imply  $S_{\psi\phi} \leq 0.25$ .

The universality hypothesis of  $\varphi_{B_s} = \varphi_{B_d}$  in [48, 19] was clearly ad hoc. Recently, in view of the enhanced value of  $S_{\psi\phi}$  at CDF and D0 a more dynamical origin of this relation has been discussed by other authors and different relations between these two phases corresponding still to a different dynamics have been discussed in the literature. Let us elaborate on this topic in more detail.

## 4.5 Facing an enhanced CPV in the $B_s$ mixing

Possibly the most important highlight in flavour physics in 2008, 2009 [15] and even more in 2010 was the enhanced value of  $S_{\psi\phi}$  measured by the CDF and D0 collaborations, seen either directly or indirectly through the correlations with various semi-leptonic asymmetries. While in 2009 and in the Spring of 2010 [16], the messages from Fermilab indicated good prospects for  $S_{\psi\phi}$  above 0.5, the recent messages from ICHEP 2010 in Paris, softened such hopes significantly [17]. Both CDF and D0 find the enhancement by only one  $\sigma$ . Yet, this does not yet preclude  $S_{\psi\phi}$  above 0.5, which would really be a fantastic signal of NP. But  $S_{\psi\phi}$  below 0.5 appears more likely at present. Still even a value of 0.2 would be exciting. Let us hope that the future data from Tevatron and in particular from the LHCb, will measure this asymmetry with sufficient precision so that we will know to which extent NP is at work here. One should also hope that the large CPV in dimuon CP asymmetry from D0, that triggered new activities, will be better understood. I have nothing to add here at present and can only refer to numerous papers [39, 49, 50, 6, 51].

Leaving the possibility of  $S_{\psi\phi} \geq 0.5$  still open but keeping in mind that also  $S_{\psi\phi} \leq 0.25$  could turn out to be the final value, let us investigate how different models would face these two different results and what kind of dynamics would be behind these two scenarios.

### 4.5.1 $S_{\psi\phi} \geq 0.5$

Such large values can be obtained in the RSc model due to KK gluon exchanges and also heavy neutral KK electroweak gauge boson exchanges. In the supersymmetric flavour model with the dominance of right-handed currents like the AC model, double Higgs penguins constitute the dominant NP contributions responsible for  $S_{\psi\phi} \geq 0.5$ , while in the RVV2 model where NP left-handed current contributions are equally important, also gluino boxes are relevant. On the operator level, it is LR *scalar* operator which is primarily responsible for this enhancement.

Interestingly the SM4 having only  $(V - A) * (V - A)$  operators is also capable in obtaining high values of  $S_{\psi\phi}$  [22, 23, 25] but not as easily as the RSc, AC and RVV2 models. The lower scales of NP in the SM4 relative to the latter models and the non-decoupling effects of  $t'$

compensate to some extent the absence of LR scalar operators. In the LHT model where only  $(V - A) * (V - A)$  operators are present and the NP enters at higher scales than in the SM4,  $S_{\psi\phi}$  above 0.5 is out of reach [52].

All these models contain new sources of flavour and CP violation and it is not surprising that in view of many parameters involved large values of  $S_{\psi\phi}$  can be obtained. The question then arises whether strongly enhanced values of this asymmetry would uniquely imply new sources of flavour violation beyond the MFV hypothesis. The answer to this question is as follows:

- In models with MFV and FBPhs set to zero,  $S_{\psi\phi}$  remains indeed SM-like.
- In supersymmetric models with MFV and non-vanishing FBPhs and in the FBMSSM, at both small and large  $\tan\beta$ , the supersymmetry constraints do not allow values of  $S_{\psi\phi}$  visibly different from the SM value [32, 50]
- In the 2HDM $_{\overline{\text{MFV}}}$  in which at one-loop both Higgs doublets couple to up- and down-quarks, the interplay of FBPh with the CKM matrix allows to obtain  $S_{\psi\phi} \geq 0.5$  while satisfying all existing constraints [14].

In the presence of a large  $S_{\psi\phi}$  the latter model allows also for a simple and unique softening of the  $\varepsilon_K$ -anomaly and of the tensions in the UT analysis if the FBPh in the Yukawa interactions are the dominant source of new CPV. In this case the NP phases  $\varphi_{B_s}$  and  $\varphi_{B_d}$  are related through

$$\varphi_{B_d} \approx \frac{m_d}{m_s} \varphi_{B_s} \approx \frac{1}{17} \varphi_{B_s}, \quad (3)$$

in visible contrast to the hypothesis  $\varphi_{B_s} = \varphi_{B_d}$  of [48, 19]. Thus in this scenario large  $\varphi_{B_s}$  required to obtain values of  $S_{\psi\phi}$  above 0.5 imply a unique small shift in  $S_{\psi K_S}$  that allows to lower  $S_{\psi K_S}$  from 0.74 down to 0.70, that is closer to the experimental value  $0.672 \pm 0.023$ . This in turn implies that it is  $\sin 2\beta = 0.74$  and not  $S_{\psi K_S} = 0.67$  that should be used in calculating  $\varepsilon_K$  resulting in a value of  $\varepsilon_K \approx 2.0 \cdot 10^{-3}$  within one  $\sigma$  from the experimental value. The direct Higgs contribution to  $\varepsilon_K$  is negligible because of small masses  $m_{d,s}$ . We should emphasize that once  $\varphi_{B_s}$  is determined from the data on  $S_{\psi\phi}$  by means of (2), the implications for  $\varepsilon_K$  and  $S_{\psi K_S}$  are unique. It is remarkable that such a simple set up allows basically to solve all these tensions provided  $S_{\psi\phi}$  is sufficiently above 0.5. The plots of  $\varepsilon_K$  and  $S_{\psi K_S}$  versus  $S_{\psi\phi}$  in [14] show this very transparently.

#### 4.5.2 $S_{\psi\phi} \approx 0.25$

Yet, as signalled recently by CDF and D0 data [17],  $S_{\psi\phi}$  could be smaller. In this case all non-MFV models listed above can reproduce such values and in particular this time also the LHT model [52] and another supersymmetric flavour model (AKM) analysed by us stay alive [32].

Again MSSM-MFV cannot reproduce such values. On the other hand the 2HDM $_{\overline{\text{MFV}}}$  can still provide interesting results. Yet as evident from the plots in [14] the FBPh in Yukawa interactions cannot now solve the UT tensions. Indeed the relation in (3) precludes now any interesting effects in  $\varepsilon_K$  and  $S_{\psi K_S}$ :  $S_{\psi\phi}$  and the NP phase  $\varphi_{B_s}$  are simply too small. Evidently, this time the relation

$$\varphi_{B_d} = \varphi_{B_s} \quad (4)$$

would be more appropriate.

Now, the analyses in [49, 50] indicate how such a relation could be obtained within the  $2\text{HDM}_{\overline{\text{MFV}}}$ . This time the FBPh in the Higgs potential are at work, the relation in (4) follows and the plots of  $\varepsilon_K$  and  $S_{\psi K_S}$  versus  $S_{\psi\phi}$  are strikingly modified: the dependence is much stronger and even moderate values of  $S_{\psi\phi}$  can solve all tensions. This time not scalar LR operators but scalar LL operators are responsible for this behaviour.

Presently it is not clear which relation between  $\varphi_{B_s}$  and  $\varphi_{B_d}$  fits best the data but the model independent analysis of [49] indicates that  $\varphi_{B_s}$  should be significantly larger than  $\varphi_{B_d}$ , but this hierarchy appears to be smaller than in (3). Therefore as pointed out in [21] in the  $2\text{HDM}_{\overline{\text{MFV}}}$  the best agreement with the data is obtained by having these phases both in Yukawa interactions and the Higgs potential, which is to be expected in any case. Which of the two flavour-blind CPV mechanisms dominates depends on the value of  $S_{\psi\phi}$ , which is still affected by a sizable experimental error, and also by the precise amount of NP allowed in  $S_{\psi K_S}$ .

Let us summarize the dynamical picture behind an enhanced value of  $S_{\psi\phi}$  within  $2\text{HDM}_{\overline{\text{MFV}}}$ . For  $S_{\phi\phi} \geq 0.7$  the FBPh in Yukawa interactions are expected to dominate. On the other hand for  $S_{\phi\phi} \leq 0.25$  the FBPh in the Higgs potential are expected to dominate the scene. If  $S_{\psi\phi}$  will eventually be found somewhere between 0.3 and 0.6, a hybrid scenario analyzed in [21] would be most efficient although not as predictive as the cases in which only one of these two mechanism is at work.

## 4.6 Implications of an enhanced $S_{\psi\phi}$

### 4.6.1 Preliminaries

Let us then assume that indeed  $S_{\psi\phi}$  will be found to be significantly enhanced over the SM value. The studies of different observables in different models allow then immediately to make some concrete predictions on a number of observables which makes it possible to distinguish different models. This is important as  $S_{\psi\phi}$  alone is insufficient for this purpose.

In view of space limitations I will discuss here only the implications for  $B_{s,d} \rightarrow \mu^+\mu^-$  and  $K \rightarrow \pi\nu\bar{\nu}$  decays, which we declared to be the superstars of the coming years. Subsequently I will make brief comments on a number of other superstars: EDMs,  $(g-2)_\mu$ , lepton flavour violation and  $\varepsilon'/\varepsilon$ .

### 4.6.2 $S_{\psi\phi} \geq 0.5$ Scenario

The detailed studies of several models in which such high values of  $S_{\psi\phi}$  can be attained imply the following pattern:

- In the AC model and the  $2\text{HDM}_{\overline{\text{MFV}}}$ ,  $Br(B_{s,d} \rightarrow \mu^+\mu^-)$  will be automatically enhanced up to the present upper limit of roughly  $3 \cdot 10^{-8}$  from CDF and D0. The double Higgs penguins are responsible for this correlation [14, 21, 32].
- In the SM4 this enhancement will be more moderate: up to  $(6-9) \cdot 10^{-9}$ , that is a factor of 2-3 above the SM value [23, 25].
- In the non-abelian supersymmetric flavour model RVV2,  $Br(B_{s,d} \rightarrow \mu^+\mu^-)$  can be enhanced up to a few  $10^{-8}$  but it is not uniquely implied due to the pollution of double-Higgs contributions through gluino boxes, that disturbs the correlation present in the AC model [32].

- In the RSc,  $Br(B_{s,d} \rightarrow \mu^+\mu^-)$  is SM-like independently of the value of  $S_{\psi\phi}$  [53]. If the custodial protection for  $Z$  flavour violating couplings is removed values of  $10^{-8}$  are possible [53, 54].

The question then arises what kind of implications does one have for  $Br(B_d \rightarrow \mu^+\mu^-)$ . Our studies show that

- The  $2HDM_{\overline{MFV}}$  implies automatically an enhancement of  $Br(B_d \rightarrow \mu^+\mu^-)$  with the ratio of these two branching ratios governed solely by  $|V_{td}/V_{ts}|^2$  and weak decay constants.
- This familiar MFV relation between the two branching ratios  $Br(B_{s,d} \rightarrow \mu^+\mu^-)$  is strongly violated in non-MFV scenarios like AC and RVV2 models and as seen in Fig. 5 of [1] taken from [32] for a given  $Br(B_s \rightarrow \mu^+\mu^-)$  the range for  $Br(B_d \rightarrow \mu^+\mu^-)$  can be large with the values of the latter branching ratios being as high as  $5 \cdot 10^{-10}$ .
- Interestingly, in the SM4, large  $S_{\psi\phi}$  accompanied by large  $Br(B_s \rightarrow \mu^+\mu^-)$  precludes a large departure of  $Br(B_d \rightarrow \mu^+\mu^-)$  from the SM value  $1 \cdot 10^{-10}$  [25].

We observe that simultaneous consideration of  $S_{\psi\phi}$  and  $Br(B_{s,d} \rightarrow \mu^+\mu^-)$  can already help us in eliminating some NP scenarios. Even more insight will be gained when  $Br(K^+ \rightarrow \pi^+\nu\bar{\nu})$  and  $Br(K_L \rightarrow \pi^0\nu\bar{\nu})$  will be measured:

- First of all the supersymmetric flavour models mentioned above predict by construction tiny NP contributions to  $K \rightarrow \pi\nu\bar{\nu}$  decays. This is also the case of the  $2HDM_{\overline{MFV}}$ .
- In the RSc model significant enhancements of both branching ratios are generally possible [53, 54] but not if  $S_{\psi\phi}$  is large. Similar comments would apply to the LHT model where the NP effects in  $K \rightarrow \pi\nu\bar{\nu}$  can be larger than in the RSc [52]. However, the LHT model has difficulties to reproduce a very large  $S_{\psi\phi}$  and does not belong to this scenario.
- Interestingly, in the SM4 large  $S_{\psi\phi}$ ,  $Br(K^+ \rightarrow \pi^+\nu\bar{\nu})$  and  $Br(K_L \rightarrow \pi^0\nu\bar{\nu})$  can coexist with each other [25].

#### 4.6.3 $S_{\psi\phi} \approx 0.25$ Scenario

In this scenario many effects found in the large  $S_{\psi\phi}$  scenario are significantly weakened. Prominent exceptions are

- In the SM4,  $Br(B_s \rightarrow \mu^+\mu^-)$  is not longer enhanced and can even be suppressed, while  $Br(B_d \rightarrow \mu^+\mu^-)$  can be significantly enhanced [25].
- The branching ratios  $Br(K^+ \rightarrow \pi^+\nu\bar{\nu})$  and  $Br(K_L \rightarrow \pi^0\nu\bar{\nu})$  can now be strongly enhanced in the LHT model [52] and RSc model [53, 54] with respect to the SM but this is not guaranteed.

These patterns of flavour violations demonstrate very clearly the power of flavour physics in distinguishing different NP scenarios.

## 4.7 EDMs, $(g - 2)_\mu$ and $\mu \rightarrow e\gamma$

These three observables are governed by dipole operators but describe different physics as far as CP violation and flavour violation is concerned. EDMs are flavour conserving but CP-violating,  $\mu \rightarrow e\gamma$  is CP-conserving but lepton flavour violating and finally  $(g - 2)_\mu$  is lepton flavour conserving and CP-conserving. A nice paper discussing all these observables simultaneously is [55].

In concrete models there exist correlations between these three observables of which EDMs and  $\mu \rightarrow e\gamma$  are very strongly suppressed within the SM and have not been seen to date.  $(g - 2)_\mu$  on the other hand has been very precisely measured and exhibits a  $3.2\sigma$  departure from the very precise SM value (see [56] and references therein). Examples of these correlations can be found in [32, 57]. In certain supersymmetric flavour models with non-MFV interactions the solution of the  $(g - 2)_\mu$  anomaly implies simultaneously  $d_e$  and  $Br(\mu \rightarrow e\gamma)$  in the reach of experiments in this decade.

Here I would like only to report on correlations between  $S_{\psi\phi}$  and the EDMs of the neutron, Thallium and Mercury atoms within the 2HDM<sub>MFV</sub>. The significant FBPhs required to reproduce the enhanced value of  $S_{\psi\phi}$  in this model, necessarily imply large EDMs in question. As a recent detailed analysis in [21] shows the present upper bounds on the EDMs do not forbid sizeable non-standard CPV effects in  $B_s$  mixing. However, if a large CPV phase in  $B_s$  mixing will be confirmed, this will imply hadronic EDMs very close to their present experimental bounds, within the reach of the next generation of experiments.

## 4.8 News on right-handed currents

One of the main properties of the Standard Model regarding flavour violating processes is the left-handed structure of the charged currents that is in accordance with the maximal violation of parity observed in low energy processes. Yet, the SM is expected to be only the low-energy limit of a more fundamental theory in which parity could be a good symmetry implying the existence of RH charged currents. Prominent examples of such fundamental theories are left-right symmetric models on which a rich literature exists. We have also seen that several NP models that we discussed contain RH currents.

The recent phenomenological interest in the RH currents in general, and not necessarily in the context of a given left-right symmetric model as done recently in [27, 28], originated in tensions between inclusive and exclusive determinations of the elements of the CKM matrix  $|V_{ub}|$  and  $|V_{cb}|$ . In particular it has been pointed out [29, 30, 31], that the presence of RH currents could either remove or significantly weaken some of these tensions, especially in the case of  $|V_{ub}|$ .

Assuming that RH currents provide the solution to the problem at hand, there is an important question whether the strength of the RH currents required for this purpose is consistent with other flavour observables and whether it implies new effects somewhere else that could be used to test this idea more globally.

In order to answer this question an effective theory approach for the study of RH currents has been proposed in [26]. In this approach the central role is played by a left-right symmetric flavour group  $SU(3)_L \times SU(3)_R$ , commuting with an underlying  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$  global symmetry and broken only by two Yukawa couplings. The model contains a new unitary matrix  $V_R$  controlling flavour-mixing in the RH sector and can be considered as the minimally flavour violating generalization to the RH sector. Thus bearing in mind that this model contains

non-MFV interactions from the point of view of the standard MFV hypothesis that includes only LH charged currents, we will call this model RHMFV.

A detailed analysis of this setup in [26] shows that the general structure of  $V_R$  can be determined, under plausible assumptions, from the existing tree level decays in the  $K$  and  $B_d$  systems and FCNC processes. The presence of  $(V-A)*(V+A)$  operators, whose contributions are strongly enhanced through renormalization group effects and in the case of  $\varepsilon_K$  also through chiral enhancement of their matrix elements, plays here an important role. The resulting  $V_R$  differs significantly from the CKM matrix.

As already stated above the RHMFV model goes beyond the MFV framework and new CPV phases in the RH sector allow for sizable enhancement of  $S_{\psi\phi}$  and solution of the  $\varepsilon_K$ -anomaly as well as of the  $|V_{ub}|$ -problem. The resulting “true” value of  $\sin 2\beta = 0.77 \pm 0.05$  is much larger than the measured value of  $S_{\psi K_S} = 0.672 \pm 0.023$ . Usually this problem would be solved through a negative new phase  $\varphi_{B_d}$ , however the  $\varepsilon_K$  constraint does not allow in this model for a non-negligible value of this phase. It appears then that the simultaneous explanation of the  $|V_{ub}|$ -problem, of large  $S_{\psi\phi}$  and of the data on  $S_{\psi K_S}$  is problematic through RH currents alone. Similarly in this simple setup the  $B_{s,d} \rightarrow \mu^+\mu^-$  constraints eliminate the possibility of removing the known anomaly in  $Z \rightarrow b\bar{b}$ .

On top of it, the constraint from  $B \rightarrow X_s \ell^+ \ell^-$  precludes  $B_s \rightarrow \mu^+\mu^-$  to be close to its present experimental bound. Moreover NP effects in  $B_d \rightarrow \ell^+ \ell^-$  are found generally smaller than in  $B_s \rightarrow \ell^+ \ell^-$ . Contributions from RH currents to  $B \rightarrow \{X_s, K, K^*\} \nu \bar{\nu}$  and  $K \rightarrow \pi \nu \bar{\nu}$  decays can still be significant. Most important, the deviations from the SM in these decays would exhibit a well-defined pattern of correlations.

## 4.9 Waiting for precise predictions of $\varepsilon'/\varepsilon$

The flavour studies of the last decade have shown that provided the hadronic matrix elements of QCD-penguin and electroweak penguin operators will be known with sufficient precision,  $\varepsilon'/\varepsilon$  will play a very important role in constraining NP models. We have witnessed recently an impressive progress in the lattice evaluation of  $\hat{B}_K$  that elevated  $\varepsilon_K$  to the group of observables relevant for precision studies of flavour physics. Hopefully this could also be the case of  $\varepsilon'/\varepsilon$  already in this decade.

## 5 Summary

We are at the beginning of a new decade which certainly will bring us first more detailed insights into the physics at short distance scales  $10^{-19} - 10^{-21}$ m. The interplay of high energy collider results with the flavour precision experiments will allow us to make important steps towards a New Standard Model of which Flavour Theory will be a prominent part. For the time being we have to wait for the first big discoveries at the LHC and at other machines around the world. In particular we look forward to the full performance of the flavour superstars. These notes hopefully demonstrate that we will have a lot of fun with flavour physics in this decade.

## Acknowledgements

I would like to thank the organizers for inviting me to such a pleasant conference and all my collaborators for exciting time we spent together exploring the short distance scales with the



help of flavour violating processes. In particular thanks go to Monika Blanke and Stefania Gori for reading carefully the manuscript of this paper. This research was partially supported by the Cluster of Excellence ‘Origin and Structure of the Universe’ and by the German ‘Bundesministerium für Bildung und Forschung’ under contract 05H09WOE.

## References

- [1] A. J. Buras, PoS E **PS-HEP2009** (2009) 024 [arXiv:0910.1032 [hep-ph]].
- [2] G. Isidori, Y. Nir and G. Perez, arXiv:1002.0900 [hep-ph]; O. Gedalia and G. Perez, arXiv:1005.3106 [hep-ph].
- [3] N. Cabibbo, Phys. Rev. Lett. **10** (1963) 531. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49** (1973) 652.
- [4] S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D **2** (1970) 1285.
- [5] R. Fleischer and M. Gronau, Phys. Lett. B **660** (2008) 212 [arXiv:0709.4013 [hep-ph]].
- [6] A. Lenz *et al.*, arXiv:1008.1593 [hep-ph]; ckmfitter.in2p3.fr
- [7] G. D’Ambrosio, G. F. Giudice, G. Isidori and A. Strumia, Nucl. Phys. B **645** (2002) 155 [arXiv:hep-ph/0207036].
- [8] A. J. Buras, P. Gambino, M. Gorbahn, S. Jager and L. Silvestrini, Phys. Lett. B **500** (2001) 161 [arXiv:hep-ph/0007085]. A. J. Buras, Acta Phys. Polon. B **34** (2003) 5615 [arXiv:hep-ph/0310208].
- [9] A. L. Kagan, G. Perez, T. Volansky and J. Zupan, Phys. Rev. D **80** (2009) 076002 [arXiv:0903.1794 [hep-ph]].
- [10] G. Colangelo, E. Nikolidakis and C. Smith, Eur. Phys. J. C **59** (2009) 75 [arXiv:0807.0801 [hep-ph]].
- [11] L. Mercolli and C. Smith, Nucl. Phys. B **817** (2009) 1 [arXiv:0902.1949 [hep-ph]].
- [12] P. Paradisi and D. M. Straub, Phys. Lett. B **684** (2010) 147 [arXiv:0906.4551 [hep-ph]].
- [13] J. R. Ellis, J. S. Lee and A. Pilaftsis, Phys. Rev. D **76** (2007) 115011 [arXiv:0708.2079 [hep-ph]].
- [14] A. J. Buras, M. V. Carlucci, S. Gori and G. Isidori, arXiv:1005.5310 [hep-ph].
- [15] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100** (2008) 161802 [arXiv:0712.2397 [hep-ex]]. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **101** (2008) 241801 [arXiv:0802.2255 [hep-ex]].
- [16] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. D **82** (2010) 032001 [arXiv:1005.2757 [hep-ex]]. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **105** (2010) 081801 [arXiv:1007.0395 [hep-ex]].
- [17] T. Aaltonen *et al.* [CDF Collaboration], CDF public notes, 9458, 10206. V. M. Abazov *et al.* [D0 Collaboration], D0 Conference note 6098.
- [18] E. Lunghi and A. Soni, Phys. Lett. B **666** (2008) 162 [arXiv:0803.4340 [hep-ph]].
- [19] A. J. Buras and D. Guadagnoli, Phys. Rev. D **78**, 033005 (2008) [arXiv:0805.3887 [hep-ph]]; Phys. Rev. D **79** (2009) 053010 [arXiv:0901.2056 [hep-ph]].
- [20] B. Batell and M. Pospelov, arXiv:1006.2127 [hep-ph].
- [21] A. J. Buras, G. Isidori and P. Paradisi, arXiv:1007.5291 [hep-ph].
- [22] W. S. Hou, M. Nagashima and A. Soddu, Phys. Rev. D **72** (2005) 115007 [arXiv:hep-ph/0508237]. Phys. Rev. D **76** (2007) 016004 [arXiv:hep-ph/0610385].
- [23] A. Soni, A. K. Alok, A. Giri, R. Mohanta and S. Nandi, Phys. Lett. B **683** (2010) 302 [arXiv:0807.1971 [hep-ph]]. A. Soni, A. K. Alok, A. Giri, R. Mohanta and S. Nandi, arXiv:1002.0595 [hep-ph].
- [24] M. Bobrowski, A. Lenz, J. Riedl and J. Rohrwild, Phys. Rev. D **79** (2009) 113006 [arXiv:0902.4883 [hep-ph]]. O. Eberhardt, A. Lenz and J. Rohrwild, arXiv:1005.3505 [hep-ph].
- [25] A. J. Buras, B. Duling, T. Feldmann, T. Heidsieck, C. Promberger and S. Recksiegel, arXiv:1002.2126 [hep-ph]; JHEP **1007** (2010) 094 [arXiv:1004.4565 [hep-ph]]. A. J. Buras, B. Duling, T. Feldmann, T. Heidsieck and C. Promberger, arXiv:1006.5356 [hep-ph].
- [26] A. J. Buras, K. Gemmler and G. Isidori, arXiv:1007.1993 [hep-ph].

- [27] A. Maiezza, M. Nemevsek, F. Nesti and G. Senjanovic, arXiv:1005.5160 [hep-ph].
- [28] D. Guadagnoli and R. N. Mohapatra, arXiv:1008.1074 [hep-ph].
- [29] A. Crivellin, Phys. Rev. D **81** (2010) 031301 [arXiv:0907.2461 [hep-ph]].
- [30] C. H. Chen and S. h. Nam, Phys. Lett. B **666** (2008) 462 [arXiv:0807.0896 [hep-ph]].
- [31] R. Feger, V. Klose, H. Lacker, T. Lueck and T. Mannel, arXiv:1003.4022 [hep-ph].
- [32] W. Altmannshofer, A. J. Buras, S. Gori, P. Paradisi and D. M. Straub, Nucl. Phys. B **830** (2010) 17 [arXiv:0909.1333 [hep-ph]].
- [33] Z. Lalak, S. Pokorski and G. G. Ross, arXiv:1006.2375 [hep-ph].
- [34] E. Dudas, G. von Gersdorff, J. Parmentier and S. Pokorski, arXiv:1007.5208 [hep-ph].
- [35] S. L. Glashow and S. Weinberg, Phys. Rev. D **15** (1977) 1958.
- [36] E. A. Paschos, Phys. Rev. D **15** (1977) 1966.
- [37] F. J. Botella, G. C. Branco and M. N. Rebelo, Phys. Lett. B **687** (2010) 194 [arXiv:0911.1753 [hep-ph]].
- [38] A. Pich and P. Tuzon, Phys. Rev. D **80** (2009) 091702 [arXiv:0908.1554 [hep-ph]]. M. Jung, A. Pich and P. Tuzon, arXiv:1006.0470 [hep-ph].
- [39] B. A. Dobrescu, P. J. Fox and A. Martin, Phys. Rev. Lett. **105** (2010) 041801 [arXiv:1005.4238 [hep-ph]].
- [40] C. B. Braeuninger, A. Ibarra and C. Simonetto, Phys. Lett. B **692** (2010) 189 [arXiv:1005.5706 [hep-ph]].
- [41] A. J. Buras, arXiv:hep-ph/9806471.
- [42] J. Brod and M. Gorbahn, arXiv:1007.0684 [hep-ph].
- [43] J. Brod, M. Gorbahn and E. Stamou, arXiv:1009.0947 [hep-ph].
- [44] D. J. Antonio *et al.* [RBC Collaboration and UKQCD Collaboration], Phys. Rev. Lett. **100** (2008) 032001 [arXiv:hep-ph/0702042]. C. Aubin, J. Laiho and R. S. Van de Water, Phys. Rev. D **81** (2010) 014507 [arXiv:0905.3947 [hep-lat]]. T. Bae *et al.*, arXiv:1008.5179 [hep-lat].
- [45] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, arXiv:1008.4884 [hep-ph].
- [46] See the talk by Cecilia Tarantino at ICHEP 2019 and [www.utfit.org](http://www.utfit.org)
- [47] A. J. Buras, D. Guadagnoli and G. Isidori, Phys. Lett. B **688** (2010) 309 [arXiv:1002.3612 [hep-ph]].
- [48] P. Ball and R. Fleischer, Eur. Phys. J. C **48** (2006) 413 [arXiv:hep-ph/0604249].
- [49] Z. Ligeti, M. Papucci, G. Perez and J. Zupan, arXiv:1006.0432 [hep-ph].
- [50] K. Blum, Y. Hochberg and Y. Nir, arXiv:1007.1872 [hep-ph].
- [51] C. W. Bauer and N. D. Dunn, arXiv:1006.1629 [hep-ph]. N. G. Deshpande, X. G. He and G. Valencia, arXiv:1006.1682 [hep-ph]. D. Choudhury and D. K. Ghosh, arXiv:1006.2171 [hep-ph]. C. H. Chen, C. Q. Geng and W. Wang, arXiv:1006.5216 [hep-ph]. P. Ko and J. h. Park, arXiv:1006.5821 [hep-ph]. S. F. King, arXiv:1006.5895 [hep-ph]. Y. Bai and A. E. Nelson, arXiv:1007.0596 [hep-ph]. J. Kubo and A. Lenz, arXiv:1007.0680 [hep-ph]. C. Berger and L. M. Sehgal, arXiv:1007.2996 [hep-ph]. B. Dutta, Y. Mimura and Y. Santoso, arXiv:1007.3696 [hep-ph]. S. Oh and J. Tandean, arXiv:1008.2153 [hep-ph].
- [52] M. Blanke, A. J. Buras, B. Duling, S. Recksiegel and C. Tarantino, Acta Phys. Polon. B **41** (2010) 657 [arXiv:0906.5454 [hep-ph]].
- [53] M. Blanke, A. J. Buras, B. Duling, K. Gemmler and S. Gori, JHEP **0903** (2009) 108 [arXiv:0812.3803 [hep-ph]]. M. Blanke, A. J. Buras, B. Duling, S. Gori and A. Weiler, JHEP **0903** (2009) 001 [arXiv:0809.1073 [hep-ph]].
- [54] M. Bauer, S. Casagrande, U. Haisch and M. Neubert, arXiv:0912.1625 [hep-ph].
- [55] J. Hisano, M. Nagai, P. Paradisi and Y. Shimizu, JHEP **0912** (2009) 030 [arXiv:0904.2080 [hep-ph]].
- [56] J. Prades, Acta Phys. Polon. Supp. **3** (2010) 75 [arXiv:0909.2546 [hep-ph]].
- [57] W. Altmannshofer, A. J. Buras and P. Paradisi, Phys. Lett. B **669** (2008) 239 [arXiv:0808.0707 [hep-ph]].